

# CluLoR: Clustered Localized Routing for FiWi Networks

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**Abstract**—The integration of passive optical networks (PONs) and wireless mesh networks (WMNs) into Fiber-Wireless (FiWi) networks can lead to effective access networks. Existing routing schemes for FiWi networks consider mainly hop-count and delay metrics over a flat WMN node topology and do not specifically prioritize the local network structure, i.e., the local wireless-optical network gateway. In this study, we explore a simple, yet effective routing algorithm for FiWi networks with a WMN organized into zones operating on different radio channels. We examine the effects of routing the traffic into and out of a zone through one or more cluster heads. We investigate the effectiveness of localized routing that prioritizes transmissions over the local gateway to the optical network and avoids wireless packet transmissions in zones that do not contain the packet source or destination. We find that this combination of clustered and localized routing (CluLoR) gives good throughput-delay performance compared to routing schemes that transmit packets wirelessly through “transit zones” (that do not contain the packet source or destination) following minimum hop-count routing.

**Index Terms**—Cluster heads, delay-sensitive traffic, fiber-wireless (FiWi) network, localized routing.

## I. INTRODUCTION

Wireless and optical networking technologies at the early stages were deployed for different respective communication settings. Due to the fact that those technologies aim to solve different problems when they were initially developed, it is hard for one given technology to overcome many of the challenges arising in the access network area. The merging of optical access technologies with wireless access technologies by capitalizing on their respective advantages could lead to powerful solutions. Passive optical networks (PONs) connect several distributed optical network units (ONUs) at subscriber premises with a central optical line terminal (OLT) at high bandwidth of up to 10 Gbps [1]–[3] with reach extending over long distances [4]–[9]. We note that a plethora of studies has examined related TDM/WDM PONs, see e.g., [10]–[17]; however, they have high deployment costs. On the other hand, wireless mesh networks (WMNs) offer flexible communication and eliminate the need for a fiber drop to every user in the network, but offer only relatively low bandwidth, which is impacted by interference among ongoing wireless transmissions [18]–[28]. Fiber-wireless (FiWi) architectures that combine optical and

wireless network technologies could lower access network deployment cost while providing high bandwidth to the end users [29].

In this paper, we focus on the problem of peer-to-peer communication within a given wireless mesh network (WMN). Integrating an optical access network with the wireless mesh network could possibly lead to higher throughput and lower end-to-end packet delays. Without an optical access network, all traffic has to go through the WMN, which results in high network interference and in turn limits the network throughput. By combining the optical access network and the WMN to an integrated fiber and wireless (FiWi) network, the traffic could be routed from the source node in the WMN over wireless hops to a nearby gateway wireless router where it could be routed via the fiber network to a gateway wireless router near the destination node. This scenario would reduce interference in the wireless mesh network, and increase throughput between the two communicating peers.

As elaborated in Section II, many FiWi network architectures and routing protocols have been explored in the past few years [30]. To the best of our knowledge, the existing FiWi routing approaches mainly consider a “flat” topology for the WMN, i.e., the existing approaches do not consider a hierarchical clustering structure of the WMN nodes. Moreover, the specific local network structure, i.e., the closest local gateway from the WMN to the PON, has not been prioritized over multi-hop transmissions through the WMN. Clustering has proven very beneficial in purely wireless networks [31], [32]. In this article, we examine the combined effects of clustered localized routing. We consider a common WMN setting where the wireless nodes are organized into zones that operate on different radio channels [33]–[35]. We allow wireless nodes to send traffic to each other directly only when they are in the same zone. Otherwise, all traffic has to go through an assigned cluster head which in turn routes the traffic to the assigned gateway router (which in turn routes the traffic to the destination zone, possibly utilizing the optical network).

The remainder of this paper structured as follows. In Section II, we discuss the related work and recent research on FiWi networks. In Section III, we introduce the principles of clustered localized routing (CluLoR). In Section IV, we describe the simulation set-up for our evaluations of CluLoR. In Section V, we examine the effects of clustering by varying the number of cluster

heads in a zone and adding relay routers between adjacent zones. In Section VI, we examine the effects of the localized routing strategy by comparing CluLoR with an unlocalized routing benchmark that follows minimum hop-count routing. In Section VII, we evaluate how CluLoR behaves when the PON is stressed with background traffic. Section VIII concludes the paper and points out future research directions.

## II. RELATED WORK

The recent survey [36] gives an overview of hybrid optical-wireless access networks. The Hybrid Wireless-Optical Broadband-Access Network (WOBAN) Architecture [37] is a pioneering FiWi network structure. The study [37] identified FiWi networking challenges with regard to network setup (placement of ONUs, Base Stations (BSs), and OLT to minimize the cost), and efficient routing protocols. The FiWi network planning problem has been further studied in [38]. The studies [39]–[41] proposed FiWi architectures and reconfiguration algorithms in order to serve the needs of the hybrid access network users.

Some of the first studies that examined peer-to-peer communication in a FiWi network were by Zheng et al. [42], [43]. These studies noted the significance of integrating the optical networks with the mesh networks to achieve significant performance improvements in terms of overall throughput and average packet end-to-end delays. Also, a simple routing protocol was proposed based on minimum-hop-count, which includes the gateway routers to the fiber network as part of the hop count. Li et al. [44] also studied the problem of peer-to-peer communications. The main focus was on implementing a novel arrayed waveguide grating based WDM/TDM PON structure, including wavelength assignment for groups of ONUs and a decentralized dynamic bandwidth allocation (DBA) algorithm, that supports direct communication between the ONUs without the traffic going through the OLT which could lead to improved end-to-end delay and throughput. Similarly, studies [45], [46] focused on inter-ONU communications by deploying a star coupler (SC) at the remote node (RN) to broadcast the packets of one ONU to all other ONUs, while [47] focused on the medium access control problem in radio-over-fiber networks. A WDM EPON that supports inter-ONU communications in which the polling cycle is divided into two sub-cycles was proposed in [48]. In this study, which is focused on FiWi routing, we consider a TDM PON with interleaved polling with adaptive cycle time (IPACT) with gated service dynamic bandwidth allocation [49], [50].

Routing protocols and algorithms for FiWi access networks have been the main focus of several studies, whereby some focus on routing the packets in the wireless front-end only, or routing the packets through the wireless and optical domains combined to achieve better performance. Early work that focused on routing algorithms in FiWi access networks includes the Delay-Aware Routing Algorithm (DARA) [51], Delay-Differentiated Rout-

ing Algorithm [52], Capacity-and-Delay-Aware Routing (CaDAR) [53], and Risk-And-Delay-Aware Routing (RADAR) [54]. Other recent studies on routing techniques in hybrid wireless-optical access network have focused on energy efficient routing [55], and Availability-Aware routing [56] as well as analytical frameworks for capacity and delay evaluation [57]. Most of these studies approach the routing as an optimization problem in order to find the optimum solution. However, all of them considered a flat topology, without a cluster structure, in the WMN. In contrast, this study focuses on the effects of clustered localized routing in the WMN on FiWi network performance.

A number of other studies have focused mainly on load balancing and Transmission Control Protocol (TCP) related issues in FiWi networks. Shaw et al. [58] proposed an integrated routing algorithm that adapts to the changes of the traffic demands within different regions of the wireless network in order to achieve load balancing in the hybrid network. The route assignment is located in the central hub. A hybrid TDM/WDM network with a wavelength assignment scheme that focuses on assigning a minimum number of wavelength to each group of ONUs while the maximum throughput at the ONUs is maintained was examined in [59]. The performance of multipath routing in FiWi and its effect on TCP performance due to out-of-order packets at the destination node was analyzed in [60], [61]. An integrated flow assignment and packet re-sequencing approach that obtains the probabilities of sending along the different paths with the objective of reducing the arrived out-of-order packets at the OLT was explored in [60]. A DBA technique that gives higher priority to the flows that trigger TCP fast retransmissions was proposed in [61]. We do not specifically examine TCP traffic; instead, we focus on traffic transmitted with the User Datagram Protocol (UDP).

We note for completeness that recently energy efficiency in FiWi access network has begun to attract research interest, see e.g., [62]–[66]. Survivability and protection techniques in FiWi access networks have been studied in [39], [67]–[73], while network coding in FiWi access network has been explored in [74], [75].

In summary, complementary to the existing FiWi networking literature, this study focuses on the effects of a combining (i) routing over cluster heads with (ii) prioritizing transmissions to be routed through the local WMN-PON gateway on overall FiWi network performance. While the existing FiWi routing literature has mainly considered a “flat” topology without a clustering structure of the wireless nodes, clustering techniques have been extensively studied in the area of purely wireless networking, see e.g., [31], [32]. To the best of our knowledge clustered routing in a FiWi network has so far only been studied in [76], which focused on the distribution of traffic in the downstream direction. The present study is the first to examine the benefits of clustered localized routing for peer-to-peer traffic involving both upstream and downstream PON transmissions in a FiWi network.

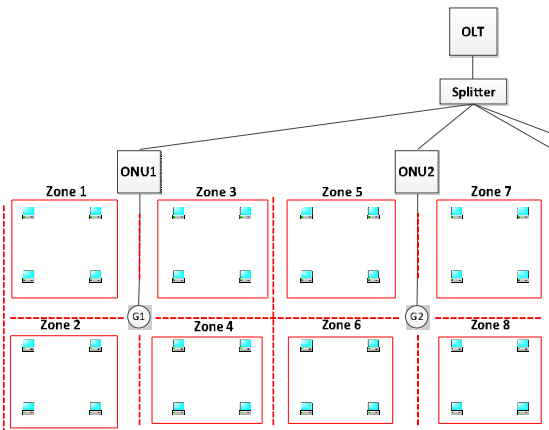


Figure 1. FiWi network structure: Wireless nodes are organized into different zones that operate on different radio frequencies (channels).

### III. PRINCIPLES OF CLUSTERED LOCALIZED ROUTING (CLUFOR)

We focus on a setting where the wireless stations (nodes), which could be WiFi routers (e.g., IEEE 802.11g WiFi routers) are organized into different zones, as illustrated in Fig. 1. Each zone operates on a different radio channel than its neighboring zones [33]–[35]. There is a single gateway router that serves the zone closest to it, e.g., zones 1–4 in Fig. 1 are served by gateway router G1. Each gateway router has an Ethernet interface that is connected directly to an ONU. Within this network setting, we examine the two principles of clustered and localized routing that are outlined in the next two subsections and combined to form the CluLoR scheme.

#### A. Clustered Routing

In each zone, there is a node that is assigned as a cluster head, as illustrated in the upper left illustration in Fig. 2. (It is possible to have multiple cluster heads for a zone, but for ease of exposition, we initially focus on the case of one cluster head per zone.) The cluster head of a zone is the node that is located closest to the gateway router. The cluster head is responsible for routing outbound packets from the regular wireless nodes in the zone on to the gateway router and for routing inbound packets from the gateway router on to the wireless nodes in the zone.

#### B. Localized Routing

The routing between the wireless nodes (peers) proceeds according to the following three rules, which are summarized in the pseudo-code in Table I: (i) If the communicating peers are within the same zone, then the packet is directly wirelessly transmitted to the destination peer without going through a cluster head or gateway router. (ii) If the zone of the destination peer is serviced by the same gateway router as the zone of the source peer, then the packet is routed by the gateway router to the destination zone without going through the optical network. (iii) If the destination zone is not served by

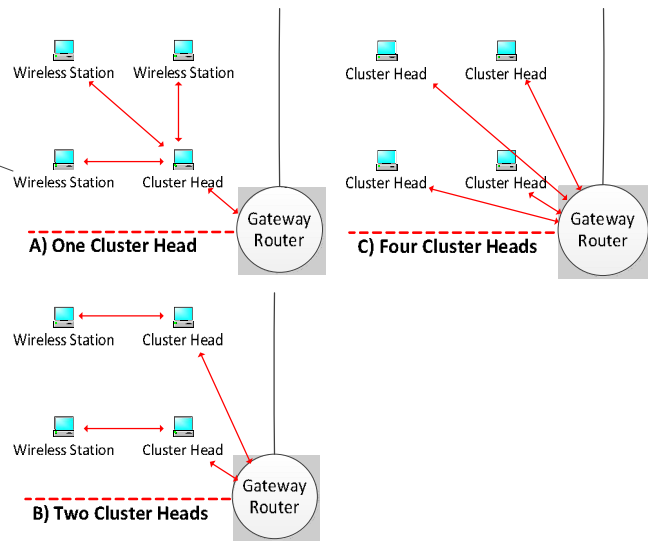


Figure 2. Illustration of clustered routing with different numbers of cluster heads in a zone: Wireless nodes direct all communication with nodes outside the zone through a cluster head. The cluster head(s) communicates with the gateway router, which is connected to an ONU. The configuration with 4 heads corresponds effectively to an unclustered benchmark as all nodes communicate directly (without going through a cluster head) with the gateway router.

TABLE I.  
PSEUDO-CODE SUMMARY OF LOCALIZED ROUTING WITHOUT  
RELAYS AT DIFFERENT TYPES OF NETWORK NODES.

```

Wireless Station - not a Cluster Head:
if (destination in the same Zone)
  Send packet directly to destination;
else
  Send packet to closest Cluster Head;

Wireless Station - Cluster Head:
if (destination in the same Zone)
  Send packet directly to destination;
else
  Send packet to Gateway Router;

Gateway Router:
if (destination in a Zone associated
  with the same Gateway Router)
  Send packet to Cluster Head associated
  with the destination wireless station;
else
  Send packet to Optical Network;

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the same gateway router as the source zone, then the packet is routed through the cluster head to the source-zone gateway router, then to the optical network.

The optical network broadcasts the packet in the downstream direction, whereby the ONU connected to the destination gateway (gateway router that is closest to the destination zone) accepts it while the other ONUs discard the packet. The destination gateway router then routes the packet via the cluster head to the destination peer in the destination zone. Localized routing ensures that a packet is never wirelessly transmitted in a zone that does not contain the source or destination of the packet.

TABLE II.  
QUAD MODE PAYLOAD SIZES

Ethernet encapsulated packet size	Payload size (UDP level)	Probability
64 bytes	18 bytes	60%
300 bytes	254 bytes	4%
580 bytes	534 bytes	11%
1518 bytes	1472 bytes	25%

IV. SIMULATION SETUP

In our simulations, we evaluate mean end-to-end packet delay and throughput of CluLoR in a FiWi network. The simulations are conducted in OMNeT++ 4.2.2 using INETMANET-2.0 modules. Specifically, we initially simulate a FiWi network with 64 wireless nodes and 4 gateway routers. The wireless nodes are placed uniformly in a 1600 m × 300 m region. The 64 wireless nodes are distributed evenly in 16 zones (4 nodes in each zone) resulting in each gateway managing 4 zones. Each of the 4 wireless gateway routers (IEEE 802.11g) is connected to its own ONU through an Ethernet cable with a transmission rate of 1 Gbps. All the ONUs are at a distance of around 20 km from the OLT.

Each wireless node is equipped with a single radio interface. The gateway routers are equipped with four different radio interfaces (4 radio channels), whereby each channel is assigned to a single zone that operates on the given radio channel. There are 11 different radio channels possible, whereby a given channel is reused in the furthest zones in order to minimize interference. We employ a log-distance path loss channel model with a path loss alpha value of 2. The radio sensitivity is set to -85 dBm and the signal-to-noise ratio threshold is set to 4 dB, whereby the received packet is considered noise if it is below that value. The transmitting power for the wireless routers is set to 20 mW in order for the router that is located furthest in the zone to reach the gateway router. The transmission range is around 250 m. The physical data rate is 54 Mb/s. The retransmit limit for the wireless LAN is set to its default value 7. The buffer size for the wireless interface is set to 1000 packets regardless of the packet size.

We use a quad mode model of payload sizes at the UDP level in order to reach the quad mode of encapsulated packet sizes at the Ethernet level [77], see Table II. The UDP level payload includes the UDP header of 8 bytes, the IP header of 20 bytes, and MAC level header of 18 bytes at the Ethernet layer. The maximum transmission unit (MTU) for the wireless interface is set to 1500 Bytes so as to avoid fragmentation. We consider independent Poisson packet generation processes in the wireless nodes, whereby all the wireless nodes have the same mean packet generation rate. For each generated packet at a given wireless node, any of the other wireless nodes in the network is selected as destination with equal probability. All simulation are run until the 95 % statistical confidence intervals of the performance measures are less than 5 % of the sample means.

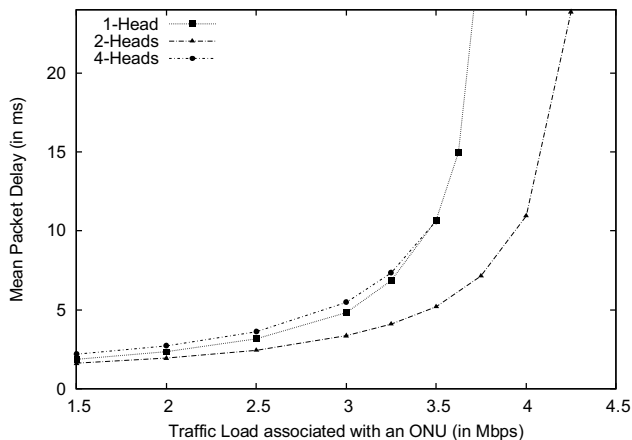


Figure 3. Clustered Routing: Mean end-to-end packet delay for different numbers of cluster heads in a zone.

V. CLUSTERED ROUTING: IMPACT OF NUMBER OF CLUSTER HEADS

A. Clustered Routing Without Relay Routers

In this section we examine the impact of the number of cluster heads in a given zone on the delay and throughput performance. We do not consider relay routers in this section; these are considered in Section V-B. As described in Section IV, the simulated wireless network is organized into different zones, whereby each zone has 4 wireless nodes. In each of the zones there is one wireless node (or multiple wireless nodes) that is (are) assigned as the cluster head (heads) of the zone and is (are) responsible for relaying the traffic from/to the gateway router. We examine the effects of having 1, 2, or 4 cluster heads (which we refer to as “heads” for brevity) in the zone, as illustrated in Fig. 2.

In the case of 1 head, the head is assigned as the wireless node that is located closest to the gateway router. In the case of 2 heads, the two wireless nodes in the zone that are closest to the gateway router are assigned as the heads. Ties in distance are broken through random selection. The outbound traffic from the other wireless nodes (that are not designated as heads) in a given zone is transmitted to the closest head; the head in turn transmits the traffic to the gateway router. Analogously, the inbound traffic is routed from the gateway router to the head that is closest to the destination node and then onwards by the head to the destination. In the case of 4 heads in a zone, all the wireless nodes in a zone are designated as heads and send their traffic directly to the gateway router. Note that the 4-head case is equivalent to unclustered routing in that all wireless nodes communicate directly with their gateway router, without a cluster hierarchy in the zone.

1) *Delay Performance:* Figure 3 shows the mean end-to-end packet delay in the FiWi network for 1, 2, or 4 heads in a zone. (The 95 % confidence intervals are too small to be visible and are omitted.) For each configuration of heads, the network traffic load is incremented until buffer overflows begin to occur; buffer overflows

are examined in detail in Section V-A.2. We observe from the figure that assigning 2-heads in the zone gives lower delays compared to the 1-head or 4-heads cases. In addition, we observe from Fig. 3 that at low loads, 1 head gives lower mean delays than 4 heads. These performance characteristics are mainly due to a trade-off between mean hop-count and transmission distance. In particular, a smaller mean hop-count implies that a packet is transmitted on average fewer times on its way from source to destination. Clearly, fewer transmissions are generally preferable as each transmission requires networking resources and incurs delay.

In the configuration with 4-heads in a zone (i.e., effectively the unclustered scenario, see Fig. 2), all four wireless nodes in a zone send directly packets to the gateway, i.e., all packets originating from the zone need only one hop to reach the gateway. Similarly, all packets arriving to the gateway for delivery to a node in the zone, reach their destination with one hop. Notice that the 4-heads configuration has the minimum mean hop-count among the three configurations illustrated in Fig. 2. As the number of heads decreases, the mean hop count increases. Specifically, the 1-head configuration requires one hop to reach the gateway from the head, but two hops to reach the gateway from any other node in the zone. Thus, to summarize, the 1-head configuration has the highest mean hop-count, the configuration with 2 heads has a moderate mean hop-count, and the 4-heads configuration has the lowest mean hop-count.

The transmission distance directly affects the received signal-to-interference and noise ratio (SINR), with transmissions propagating over longer distances being received with lower SINR. Among the considered configurations, see Fig. 2, the 4-heads configuration has the longest propagation distances, as all nodes in the zone transmit directly to and receive directly from the gateway router. Especially the propagation distance from the node in the upper left corner in the 4-heads illustration to the gateway router in Fig. 2 is the longest propagation distance among any of the three considered configurations. This long-distance transmission is particularly vulnerable to failure due to low SINR and requiring retransmissions. Notice from Fig. 2 that in comparison with the 4-heads configuration, the 1-head and 2-heads configurations both have moderate propagation distances, i.e., only moderate chances of a packet transmission being unsuccessful due to low SINR.

Returning to the interpretation of the results in Fig. 3, we note that the 4-heads configuration incurs the highest mean packet delay mainly due to the long propagation distances and the resulting packet transmission failures due to low SINR and packet re-transmissions. The lower mean-hop count cannot overcome the disadvantage of the long propagation delays and results in relatively frequent packet failures and retransmissions, which dominate the delay characteristics.

In the configuration with 1 head, the propagation distances are shorter, reducing the probability of packet failure due to low SINR. Thus, mean packet delays are

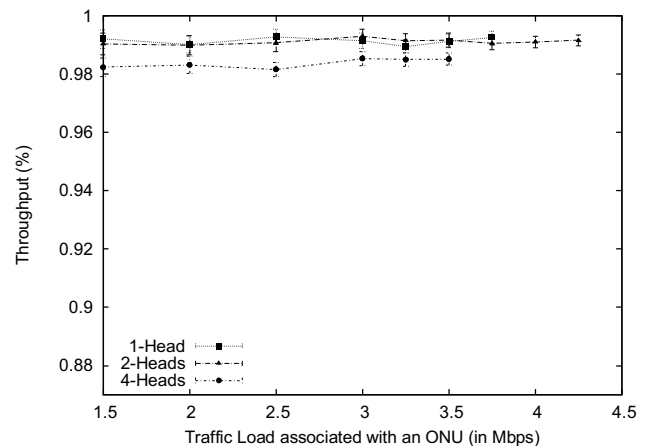


Figure 4. Clustered routing: Normalized throughput for different numbers of heads

slightly reduced compared to the 4-heads configuration. But transmissions from/to 3 wireless nodes in the zone require two hops to reach/come from the gateway router.

The configuration with 2 heads strikes a good balance between low mean-hop count and short propagation distances (i.e., high SINR) achieving the lowest mean packet delays in Fig. 3. The 2-heads configuration has similarly short propagation distances for transmissions from/to the wireless nodes in the zone as the 1-head configuration. At the same time, the 2-heads configuration has a lower mean-hop count than the 1-head configuration, since the transmissions from/to one more node in the zone, i.e., the second head, require only one hop to reach/come in from the gateway router.

2) *Throughput Performance:* Figure 4 shows the 95 % confidence intervals of the normalized mean (long-run average) throughput in terms of traffic that reaches its final destination. The traffic load is incremented until buffer overflows occur; for each curve, the rightmost point corresponds to the highest traffic load without buffer overflows. The average throughput is measured based on the number packets with their corresponding numbers of bits that are received by the destination wireless nodes. The packets (bits) received by intermediate cluster heads and gateway routers are not taken into account.

We observe from Fig 4 that the mean throughput is statistically the same for 1 head and 2 heads in the zone, whereby they both have higher throughput than the 4-heads configuration. We further observe that the 2-heads configuration accommodates higher traffic loads, up to about 4.25 Mbps before buffer overflows occur, whereas the 1-head configuration avoids buffer overflows only up to a load of about 3.75 Mbps. The explanations for these behaviors are as follows. First, the 4-heads case has lower average hop-count than the other two cases; however, the long transmission distance from the wireless node farthest from the gateway router has lower SINR than any transmissions in the 1-head and 2-heads cases. Thus, the farthest-away node relatively frequently requires packet retransmissions and hence reaches the maximum

retransmit limit relatively more often compared to the nodes in the 1-head and 2-heads configurations. As a result, more packets are dropped due to reaching the maximum retransmission limit in the 4-heads configuration compared to the 1-head and 2-heads configurations resulting in lower throughput for the 4-heads configuration at low to moderate traffic loads. Moreover, in the 4-heads configuration, the buffers fill up more due to more frequent packet retransmissions, leading to buffer overflows at lower traffic loads (3.5 Mbps); whereas, the 1-head and 2-heads configurations avoid buffer overflows up to 3.75 and 4.25 Mbps, respectively.

At low loads, both the 1-head and 2-heads configurations achieve similar throughput levels. This is because the (very slightly) shorter transmission distances (i.e., higher SINRs) with the 1-head configuration largely counterbalance its higher hop-count. Similarly, the (very slightly) longer transmission distances (i.e., lower SINRs) largely counterbalance the lower hop-count for the 2-heads configuration. As the traffic load grows high and buffer backlogs grow, the bottleneck in the 1 head leads to buffer overflows at a lower traffic rate compared to when 2 heads share the traffic load going wirelessly in and out of a zone. In fact, we have observed in our simulations that in the case of 2 heads, the buffer overflow first occurs at the gateway router as it wirelessly transmits all traffic destined into a zone to the two heads.

**B. Performance with Relay Routers**

Relay routers can be thought of as an extra cluster head in the zone. They are only used to relay the packets between neighboring zones, so that if the destination is in an adjacent zone, then the packet is directly transmitted to the relay router, which in turn sends the packet to the destination, as illustrated in Figure 5. The Pseudo-code for the routing algorithm is summarized in Table III. Relay routers are equipped with two different radio interfaces, which are configured to the two radio channels of the two adjacent zones. Relay routers relieve the cluster heads and the gateway routers from sending packets destined to a direct neighbor zone.

Figure 6 shows the mean packet delay with 22 relay routers added to the network configuration of Section IV and without added relay routers for the different configurations of cluster heads in a zone. We first observe that the performance with added relay routers for the different numbers of cluster heads in the zone follows the same general pattern as for the network without relays, see Section V-A. We also observe that adding relay routers results in substantially lower mean end-to-end packet delays, particularly for moderate to high traffic loads. These mean delay results illustrate the effects of bypassing the cluster heads and gateway routers, which lowers the mean hop-count. Also, the packets destined to adjacent zones avoid the queuing delays in the gateway and head routers.

Upon closer examination of Fig. 6, we notice that the relays have a slightly more pronounced effect for the 4-

**TABLE III.**  
PSEUDO-CODE SUMMARY OF LOCALIZED ROUTING WITH RELAY ROUTERS FOR THE DIFFERENT TYPES OF NETWORK NODES.

```

Wireless Station - not a Cluster Head:
if (destination in the same Zone)
    Send packet directly to destination;
else if (destination in adjacent
        Zone & share a Relay Router)
    Send packet to Relay Router;
else
    Send packet to closest Cluster Head;

Wireless Station - Cluster Head:
if (destination in the same Zone)
    Send packet directly to destination;
else if (destination in adjacent
        Zone & share a Relay Router)
    Send packet to Relay Router;
else
    Send packet to Gateway Router;

Relay Router
    Send packet to adjacent Zone

Gateway Router:
if (destination in a Zone associated
    with the same Gateway Router)
    Send packet to Cluster Head associated
    with the destination wireless station;
else
    Send packet to Optical Network;
    
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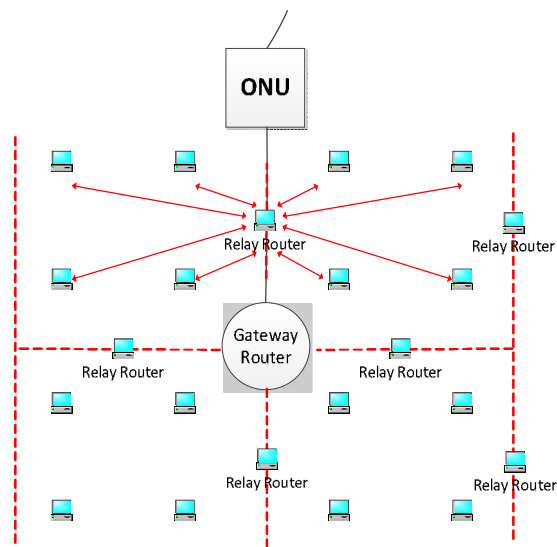


Figure 5. FiWi network structure with relays operating at the two radio frequencies of the two adjacent zones. Packets destined to an adjacent zone are routed through the relay router, bypassing the cluster heads and gateway router.

heads configuration compared to the 1-head and 2-heads configurations. This is because the average propagation distance from the wireless nodes to the relay routers is lower than to the gateway router for the 4-heads configuration. On the other hand, for the 1-head and 2-heads configurations, the propagation distances from the wireless nodes to the relay (without going through the head(s)) are somewhat longer than the distances to the cluster heads. Thus, the benefits of the relay routers

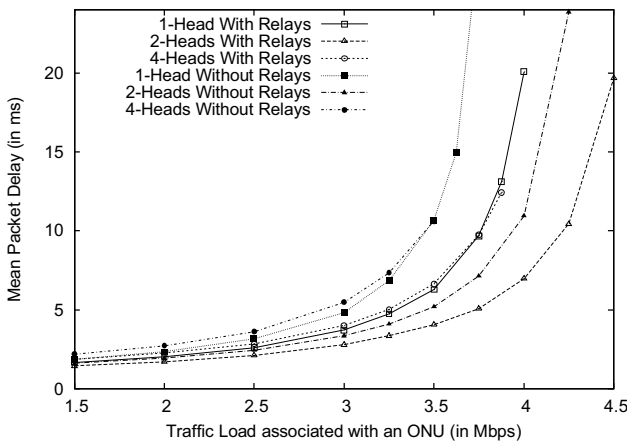


Figure 6. Clustered routing with relays: Mean packet delay as a function of traffic load for different numbers of cluster heads in a zone, with and without relays between adjacent zones.

are somewhat less pronounced with 1 or 2 cluster heads compared to the 4-heads configuration.

We observed from additional simulations for which we do not include plots to avoid clutter, that the throughput levels with relays are only very slightly elevated compared to the throughput levels without relay routers (see Fig. 4). However, the maximum traffic load that can be accommodated before buffer overflows occur is significantly increased by the relays; specifically for the 1-head configuration from 3.75 to 4 Mbps, for 2 heads from 4.25 to 4.75 Mbps, and for 4 heads from 3.5 to 3.875 Mbps.

### C. Goodput for Delay Sensitive Traffic

To obtain deeper insights into the performance of the different cluster head and relay configurations, we simulated our FiWi network with a delay sensitive application. An example of delay sensitive application is online video gaming, for which packet delays should not exceed 50 ms. Higher delays disrupt the interactions between the players making the game impossible to play. In interactive video games, many of the participating players are located in the same geographic region and thus peer-to-peer traffic in a FiWi network is a reasonable model. Figure 7 shows the goodput, i.e., the portion of the normalized throughput that arrives within the 50 ms delay limit, for the different configurations. We observe from Fig. 7 that clearly the configuration with two heads in a zone combined with relays gives the highest goodput among the considered schemes. The goodput gains with relays are especially pronounced at high traffic loads. For a load of 4.25 Mbps, for instance, the relays increase the goodput by approximately 10 % for the 2-heads configuration.

## VI. LOCALIZED ROUTING: COMPARISON WITH UNLOCALIZED MINIMUM-HOP-COUNT ROUTING

In this section we compare the performance of our proposed CluLoR with an unlocalized routing bench-

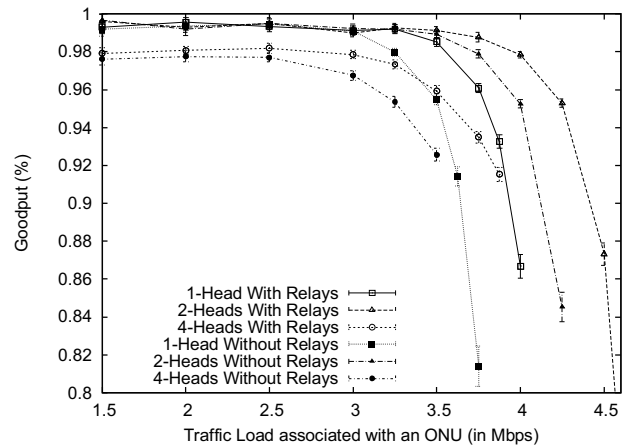


Figure 7. Clustered routing with relays: Normalized Goodput for traffic with delay limit of 50 ms

mark based on minimum-hop-count routing [42]. CluLoR transmits the traffic wirelessly only in zones that contain the source or the destination; while the traffic is routed through the fiber network from the source to the destination zone. In contrast, with unlocalized routing the traffic may be transmitted wirelessly in zones that contain neither the destination nor the source, i.e., the traffic may traverse some intermediate zones via wireless transmissions following, e.g., minimum-hop-count routing. We consider in this section the best performing clustered routing configuration from Section V, i.e., the configuration with two heads per zone and with relays.

Figure 8 illustrates CluLoR and unlocalized minimum-hop-count routing for an illustrative example with one traffic source, namely a regular wireless station, and four possible destinations. With CluLoR, the traffic is routed through the cluster head (first hop) to the gateway router (second hop), from the gateway router G1 adjacent to the source zone through the fiber network to the gateway router G2 adjacent to the destination zone (third hop), to the cluster heads (fourth hop), and regular wireless station destinations (fifth hop). Clearly, with CluLoR, the traffic is only transmitted wirelessly in a zone that includes the source or the destination; thus there is no wireless interference created in any other zones.

In contrast, unlocalized routing based on the minimum hop-count routes the traffic from the source node to the relay router between zones 1 and 2 (first hop), then the relay router transmits the packet on the wireless channel of zone 2 to reach the relay router between zones 2 and 3 (second hop), and the packet is then transmitted in turn by the relay router to reach the destinations in zone 3 (third hop).

Figure 9 compares the mean end-to-end packet delay for CluLoR with unlocalized minimum hop-count routing for the configuration with two heads per zone with relays. We observe from the figure that at lower traffic loads, the delays for both routing approaches are comparable. However, as the traffic load increases, CluLoR achieves

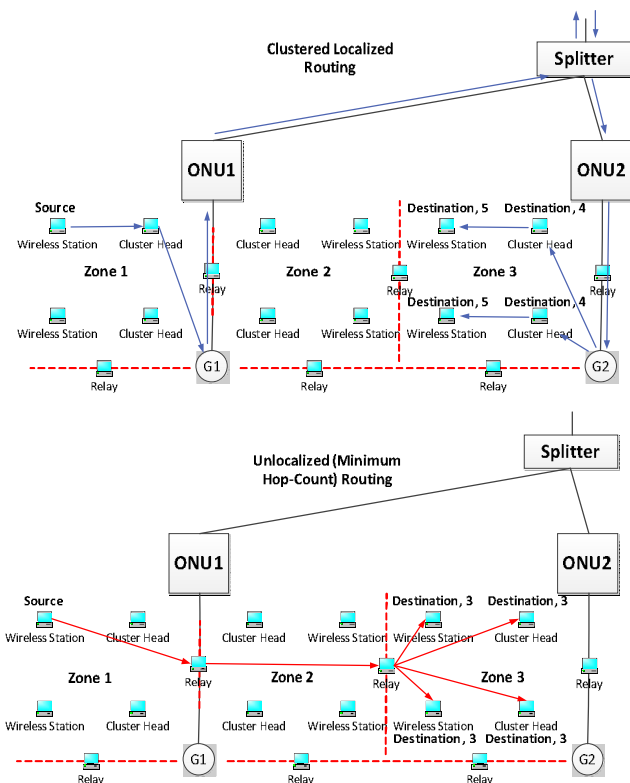


Figure 8. Illustration of clustered localized routing (CluLoR) with two heads and relays for a scenario with a regular wireless router as source: CluLoR avoids the traversal of zones that do not contain the source or destination node by routing through the fiber network. In contrast, unlocalized routing traverses zones without a source/destination (using the relays operating at both radio frequencies of adjacent zones) to achieve the minimum hop-count.

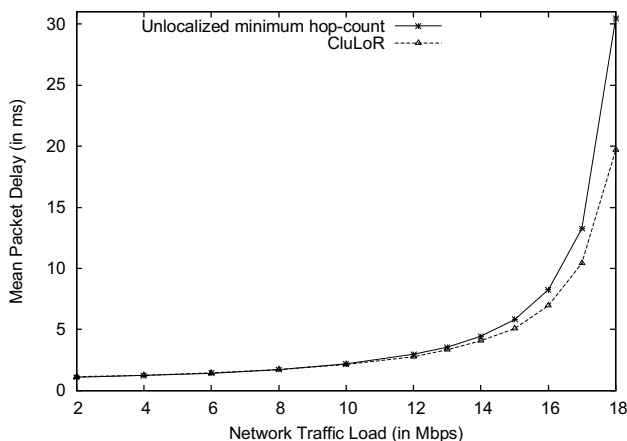


Figure 9. Localized routing: Mean packet delay for CluLoR vs. unlocalized minimum hop-count routing.

lower mean packet delays than unlocalized minimum hop-count routing. For a traffic load of 18 Mbps, the mean packet delay with CluLoR is only about two thirds of the delay with unlocalized minimum hop-count routing. The higher delay with unlocalized routing is mainly due to “transit” traffic through zones that contain neither the source nor the destination. The wireless transmissions

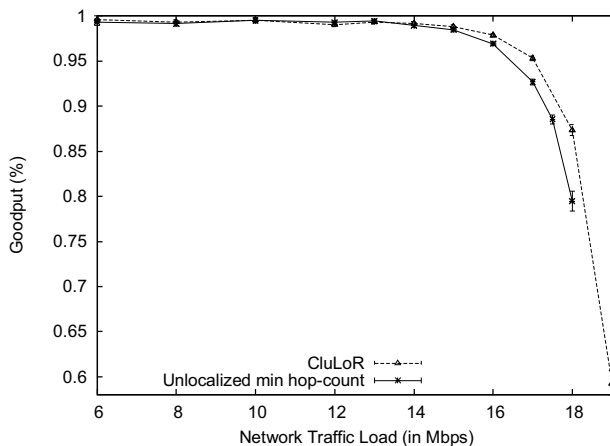


Figure 10. Localized routing: Normalized goodput for 50 ms delay limit for CluLoR vs. unlocalized minimum hop-count routing.

of this transit traffic increase the interference resulting in higher probability of packet transmissions failing due to low SINR as well as an increased chance of packet collisions. Consequently, more packet re-transmission are required, resulting in increased mean packet delays.

Both clustered localized routing and unlocalized minimum hop-count routing achieve normalized throughput levels close to 100 %, we do therefore not include a throughput plot here to avoid clutter. The only noticeable difference between CluLoR and unlocalized minimum hop-count routing is that CluLoR accommodates traffic loads up to 19 Mbps without buffer overflows compared to 18 Mbps with unlocalized routing. This behavior is mainly due to the higher interference with unlocalized routing, which causes more packets to become backlogged due to the more frequent retransmissions; hence, increasing the chance of buffer overflows.

Figure 10 compares the goodput for a delay limit of 50 ms for CluLoR with unlocalized minimum hop-count routing. We observe that clustered localized routing achieves significantly higher throughput, particularly for high traffic loads. For a traffic load of 18 Mbps, the goodput is over 8 % higher with CluLoR compared to unlocalized routing.

### VII. EVALUATION FOR HIGHLY LOADED FIBER NETWORK

So far our evaluation of CluLoR has focused on networking scenarios with only peer-to-peer traffic among the wireless stations. In this section, we add a high background traffic load that traverses only the fiber network and examine the impact on peer-to-peer traffic between the wireless stations that is routed following the CluLoR approach. More specifically, we increase the ONU traffic load by adding a wired incoming traffic component. We also increase the number of ONUs to more heavily load the PON access network.

In particular, we simulate a PON network with 32 ONUs. The ONUs are divided into 8 groups; each group



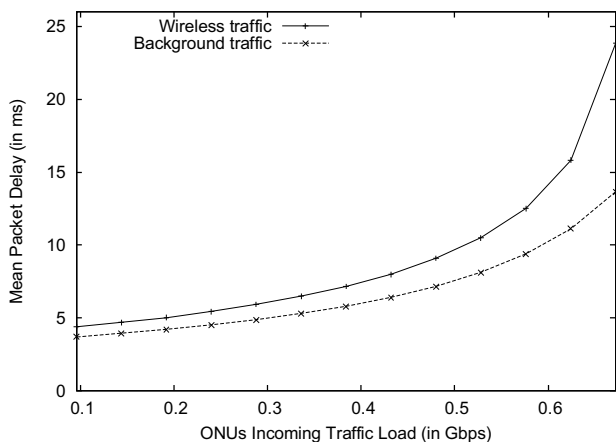


Figure 11. Mean end-to-end packet delay for PON with fiber background traffic (32 ONUs with 2:1 ratio of background traffic : peer-to-peer wireless station traffic).

has 4 ONUs. One reason for dividing the ONUs into 8 groups is to minimize the interference between the zones. Having all the 32 ONUs in one region could significantly affect the performance because wireless routers in a far-away cluster could be within the sensing range of a given cluster. The wireless nodes are uniformly distributed in a given region with a distance between each node of 50 meters. As in the set-up in Section IV, each ONU handles 16 wireless nodes. The distance separation between each region (group) of ONUs is set to be larger than 1 km. The transmission power is set to 20 mW. Each ONU is associated with 4 zones and each zone is configured with 2 cluster heads. In this section, we do not consider relay routers as our focus is to examine the impact of background traffic in the fiber network on the peer-to-peer traffic of the wireless stations. Omitting relay routers forces more of the peer-to-peer traffic through the fiber network and thus gives a worst-case assessment of the impact of fiber network background traffic.

We maintain a ratio of the incoming ONU traffic to be 2:1 for fiber network background traffic : peer-to-peer wireless node traffic. All traffic follows independent Poisson packet generation processes. For the fiber network background traffic, the destination is considered to be an Internet destination outside the PON network. We measure the delay of fiber background traffic from the instant of packet generation to the instant that the packet is completely received by the OLT.

Figure 11 shows the delay performance for background traffic and peer-to-peer wireless station traffic. The x-axis represents the total aggregate incoming traffic load at the 32 ONUs. We observe from the figure that the delays for background and peer-to-peer wireless traffic follow the same curve shape at low loads. However, for moderate to high traffic loads, a pronounced gap opens up between the wireless traffic delay and the background traffic delay. This gap grows wider with increasing traffic load.

The delay results in Fig. 11 indicate that at low traffic loads, the delays in the optical network, which is the only

network component traversed by the background traffic, dominate the wireless traffic delay. That is, the wireless transmissions to and from the gateway routers contribute relatively little to the delay experienced by the peer-to-peer wireless traffic; most of the delay comes from the PON transmissions (more specifically, the upstream transmissions, which require polling-based medium access control proceeding in polling cycles [78]). On the other hand, for high traffic loads, the probability of collisions in the random access of the wireless channels increases, which causes retransmissions that in turn increase delays. These wireless transmission delays add quite significantly to the PON delays. For a traffic load close to 0.7 Gbps, the additional wireless transmission delay experienced by the peer-to-peer wireless traffic is approximately 10 ms on top of the roughly 13 ms of the PON delay.

#### VIII. CONCLUSION & FUTURE DIRECTIONS

We have examined the combined effects of clustered and localized routing (CluLoR) in fiber-wireless (FiWi) networks. CluLoR is a simple routing strategy that does not require route discovery and maintenance between distant regions of the wireless mesh network (WMN) of a FiWi network. Instead, WMN nodes require only local routes to and from their nearby cluster heads, while in turn the cluster heads require only routes to their nearby gateway routers that interface the WMN with the fiber network.

Our evaluations for CluLoR in a FiWi network organized into zones operating on different radio channels revealed that the clustered routing strategy where regular wireless nodes communicate via cluster heads with the gateway router improves the throughput-delay performance compared to unclustered routing where wireless nodes directly communicate with the gateway router. Our evaluation of the localized routing strategy indicated substantial throughput-delay improvements over an unlocalized minimum hop-count routing strategy.

There are many important directions for future research on simple, yet effective FiWi routing strategies. One direction is to examine the integration of routing in FiWi networks with the routing in metropolitan area networks [79]–[83] that interconnect the FiWi network with the Internet backbone as well as the interoperation with modern cellular networking standards, such as LTE-Advanced [84], [85]. Another direction is to explore how to extend the networking service from the wireless nodes to their local area, e.g., the wireless nodes could support local body area or sensor networks [86]–[91] and help them to communicate over the access network.

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